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**SPRAY COMBUSTION UNDER
OSCILLATORY PRESSURE CONDITIONS**

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I. Research Objectives and Potential Impact on Propulsion

The performance and stability of liquid rocket engines is often argued to be significantly impacted by atomization and droplet vaporization processes. In particular, combustion instability phenomena may result from the interactions between the oscillating pressure field present in the rocket combustor and the fuel and oxidizer injection process. Few studies have been conducted to examine the effects of oscillating pressure fields on spray formation and its evolution under rocket engine conditions. The present study is intended to address the need for such studies. In particular, two potentially important phenomena are addressed in the present effort. The first involves the enhancement of the atomization process for a liquid jet subjected to an oscillating pressure field of known frequency and amplitude. The objective of this part of the study is to examine the coupling between the pressure field and/or the resulting periodically perturbed velocity field on the breakup of the liquid jet. In particular, transverse mode oscillations are of interest since such modes are considered of primary importance in combustion instability phenomena.

The second aspect of the project involves the effects of an oscillating pressure field on droplet coagulation and secondary atomization. The objective of this study is to examine the conditions under which phenomena following the atomization process are affected by perturbations to the pressure or velocity fields. Both coagulation and secondary atomization affect droplet vaporization processes and consequently can represent a coupling mechanism between the pressure field and the energy release process in rocket combustors. It is precisely this coupling which drives combustion instability phenomena. Consequently, the present effort is intended to provide the fundamental insights needed to evaluate these processes as important mechanisms in liquid rocket instability phenomena.

Due to the challenging measurement environment presented by these studies, a complementary diagnostic development effort has proceeded in parallel with the above studies. These diagnostic approaches are emphasizing real-time measurements of droplet size, size distribution and spatial location. Both novel, as well as state-of-the-art, techniques are presently being addressed and validated in the present experiments.

The major impact of the present study on propulsion engineering involves the potential for gaining a fundamental understanding of the role of pressure variations on atomization and spray phenomena. Through an understanding of the proposed mechanisms for combustion instability generation, the basic understanding of the underlying physics required for development of appropriate submodels can be achieved. Present rocket combustion modelling efforts suffer from the lack of appropriate

submodels for describing the interactions between spray formation and droplet processes with oscillating pressure and velocity fields. The present research program is aimed directly at resolving some of the critical elements in that process.

II. Current Status and Results

A. Jet Breakup Under Acoustic Pressure Oscillations

A sequence of experiments have been conducted to study the effects of acoustic oscillations on the breakup of liquid jets and the trajectories of the resulting droplets. Both mono-injector (water injection) and co-axial nozzles (water core; nitrogen annulus) were investigated towards this end. Experimental techniques used for this investigation involved high speed cinematography (Spin Physics camera), laser light scattering/polarization ratio techniques and simple flash photography. A new innovative technique that will be used in the near future is phase-doppler anemometry for droplet sizing. Experimental results for the mono-injector nozzles show that high frequency acoustic oscillations (1-4 kHz) play a dramatic role in the breakup of liquid jets at certain preferential modes that are characteristic of the injection chamber. These results are of potential importance for impinging-element type injectors for obvious reasons. Initial experimental results for the co-axial nozzle have shown no dramatic changes in liquid atomization characteristics. However, measurement capabilities have been limited in these initial experiments and more exhaustive consideration is to be given to effects on the droplet field in the near future. Preliminary numerical calculations indicate that the trajectories of small droplets (less than approximately 100 μm) are significantly affected both by acoustic oscillations and the phase angle of the oscillations at the moment of atomization. Numerical calculations also show that these small droplets are subjected to extremely high g-forces, which suggests that acoustic oscillations can trigger secondary atomization phenomenon.

Experimental Setup

A schematic of the cylindrical chamber used for our experiments is shown in Fig. 1. The 6 inch diameter, 24 inch steel chamber has two 120-Watt Altec-Lansing speakers attached at the ends of the speaker arms. These speakers are used to drive the acoustic modes in the chamber. The speakers can be driven with any desired phase separation and microphone measurements of the pressure field within the chamber show that peak to peak oscillations in excess of 4 psi can be maintained. Two windows, centered 6 inches from the top of the chamber provide visual access. Optionally, one of the speakers can be replaced with a window to provide additional visual access. A moveable injector as shown in Fig. 1 is used to position the injector face near the window for added visual access. Four circumferential microphone ports, at 90° intervals are located 10 inches from the top of the chamber. Microphones employed at these ports are used to study the acoustic characteristics of the chamber.

The acoustic modes of the chamber were first identified both analytically and experimentally. The standing wave frequencies were calculated by solving the 3-D wave equation by separation of variables. For the experimental identification of the standing wave frequencies, a white noise generator was used to drive the speakers and the resulting microphone responses at the various ports were analyzed. Good agreement between the calculations and experimental results were found for the simple longitudinal and tangential modes. The higher combined modes of the chamber were, however, more difficult to identify and is a reflection of the rich frequency characteristics of the chamber.

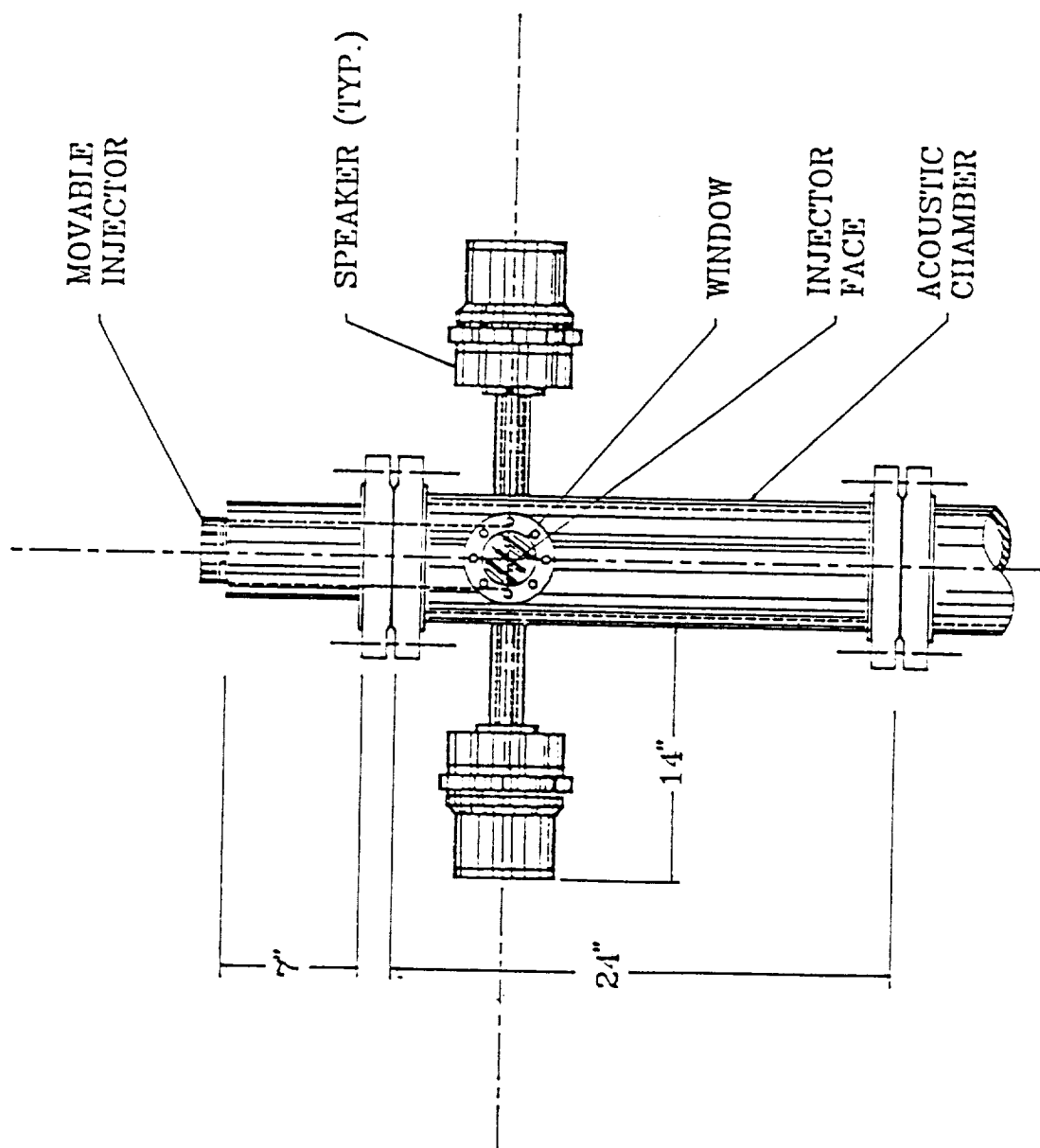


Fig. 1. A schematic of the injection chamber.

ACOUSTIC CHAMBER SCHEMATIC

Jet Breakup Results

Acoustic oscillations were visually and photographically observed to dramatically breakup the liquid jet emanating from mono-injector nozzles (0.0625 inch and 0.1 inch diameter nozzles with a length to diameter ratio in excess of 10) in two distinct fashions. The Reynolds numbers of the jets ranged from 2000 to 9000 and the corresponding Weber numbers based on the gas density ranged from 0.03 to 0.5, which places these jets in the Rayleigh breakup region. The first type of breakup occurred at 1140 Hz which corresponds to the first tangential mode. The jet was observed to breakup into a spray with droplet diameters of the same order of magnitude as the nozzle diameter. A photograph of this tangential-mode breakup is shown in Fig. 2. The corresponding pressure amplitude pattern at one phase angle measured by traversing two microphones within the chamber is shown in the inset graph. Note that the centerline of the chamber that bifurcates the speaker axis also delineates the positive and negative pressure amplitudes. This type of pressure pattern indicates that the mode is 1-T mode. It is postulated that the 1-T mode frequency couples preferentially to the breakup frequencies of the jet. The second type of breakup is shown in Fig. 3 at a frequency of 1560 Hz. For this type of breakup, the jet first acquires the shape of a two-dimensional fan (perpendicular to the speaker axis) which is reminiscent of the fan-structure observed with impinging nozzles. Droplets sheared from the bottom of the fan are visually at least more than an order of magnitude smaller than the diameter of the nozzle. Acoustic measurements of the mode in question show tangential mode-like characteristics as can be seen from the inset graph in Fig. 3. However, the sharp pressure gradient that exists along the center vertical plane of the chamber that seems to cause the jet to 'fan' out is not characteristic of a pure tangential mode. This mode could be the 3-Longitudinal/1-Tangential (calculated to be 1580 Hz) mode. Note that the pressure amplitude measurements were made 10 inches from the top of the chamber which places the measurement location close to the pressure antinode for the longitudinal component of this mode.

Conclusions

Jets emanating from mono-injector nozzles were seen to breakup under both tangential mode and mixed longitudinal/tangential acoustic modes into both spray-like and fan-like structures for physical conditions that place the jets in the Rayleigh breakup region. No effect of these modes on the gross atomization characteristics of co-axial nozzles were observed. However, calculations indicate that trajectories of droplets are affected by acoustic oscillations and it seems that measurements of droplet size and velocity in lieu with the phase angle of acoustic oscillations will unearth additional information.

B. Diagnostic Development

As a complementary effort to the atomization and spray studies described previously, a diagnostic development program has been initiated to support the measurement needs of this project.

Spray and droplet measurements in liquid rocket engines require non-intrusive

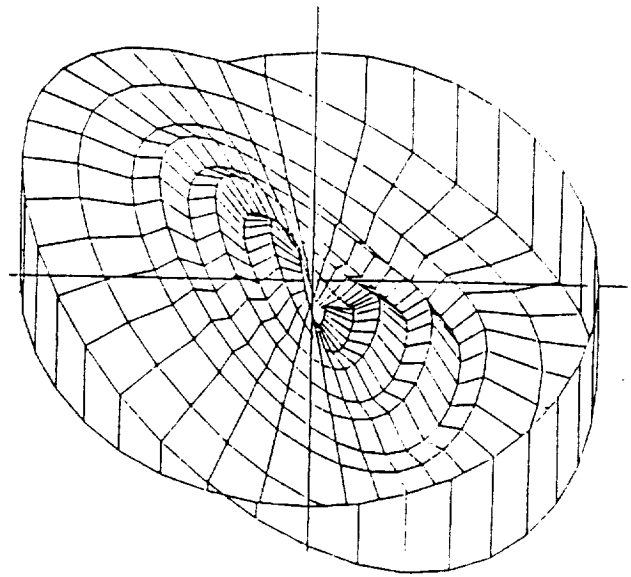


Fig. 2. Spray type breakup observed at a frequency of 1140 Hz. The inset graph shows the pressure amplitude at a horizontal plane (within the chamber) 10 inches from the top of the chamber at zero phase angle. This mode is identified to be the first tangential mode.

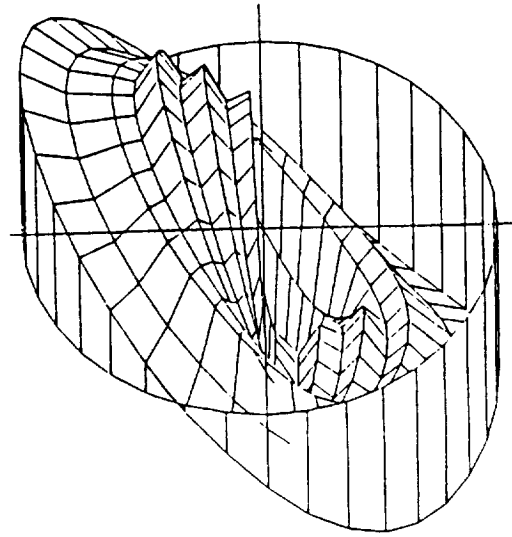


Fig 3. Fan type breakup observed at a frequency of 1560 Hz. The inset graph shows the pressure amplitude at a horizontal plane (within the chamber) 10 inches from the top of the chamber at zero phase angle. Note the high pressure gradient at the center vertical plane. This mode could be the third longitudinal/first tangential mode.

techniques which possess both high spatial and temporal resolution capabilities. In addition, due to the short duration and highly transient nature of liquid rocket combustion processes, techniques which provide extensive spatial measurement capabilities are highly desirable. Recent progress in the development of planar laser imaging techniques have demonstrated the potential for achieving such measurements. In the present work, a planar laser imaging approach for droplet and particle sizing which incorporates an optical polarization ratio technique has been investigated. A series of pressure atomized sprays have been imaged to obtain droplet size measurements based on the ratio of horizontally to vertically polarized scattered light. This technique, which provides an ensemble averaged droplet diameter, provides spatially and temporally resolved droplet size measurements over an extensive spatial region.

Experimental Setup

The polarization ratio approach utilized in these studies involves a pulsed Nd-YAG laser operating at the 532 nm laser line. This laser beam is formed into a sheet of light whose polarization orientation is adjusted using a half-wave plate to provide both vertically and horizontally polarized light components. For the water sprays studied, the polarization vector was oriented at a 45° angle with respect to the horizontal plane of polarization. The images of scattered light intensity at a 90° scattering angle were simultaneously obtained for each polarization orientation using a pair of 35 mm cameras with the aid of an appropriate beam splitter and polarization filter. The images were recorded on black and white film and were subsequently digitized using a CID solid state camera. These digitized images were stored on a personal computer and two-dimensional polarization ratio fields were constructed from the ratio of a pair of vertically and horizontally polarized scattered light images. The ratio of horizontal and vertical polarization intensity can be directly related to appropriate optical scattering cross sections (C_{HH}/C_{VV}). Droplet size information can be directly calculated from MIE light scattering theory. Calculations of these polarization ratio values were utilized to provide droplet size information throughout the spray.

Results

In the present studies, a spray region, 5 cm x 5 cm, was imaged and analyzed. Droplet sizes based on D_{32} , in the water spray were observed to vary between 10 μm in the central region of the spray to 40 μm near the edges of the spray. Comparisons with preliminary measurements utilizing a phase doppler particle sizing approach consistently show a systematic difference in size. The polarization ratio approach typically results in droplet sizes a factor of two to four smaller than the phase doppler results. In addition to providing a sizing capability, the present work demonstrates that the polarization ratio approach can be used to provide a means to discriminate regions containing soot particles from droplet regions. Such a capability will be useful in studies in liquid hydrocarbon rocket combustors where both soot particles and droplets are likely to be present.

III. Proposed Work for Coming Year

Work during the next year will concentrate on performing similar acoustic experiments in an environment that more closely matches actual rocket motors. These experiments will be carried out in a pressurized environment using the current acoustic chamber which can be operated at pressures up to 300 psi. Three types of nozzles will be used: a series of mono-injector nozzles ranging in diameter from 0.0625 inches to 0.1 inches with an aspect ratio of at least 10, a co-axial injector having an inner diameter of 0.1 inches and an outer diameter of 0.2 inches with an aspect ratio of 35, and an impinging nozzle yet to be designed. Based on past experience, the acoustic modes of interest with the current chamber will be the first tangential mode (1-T mode) at 1140 Hz and the previously discussed first tangential, third longitudinal mode (1-T/3-L mode) at 1560 Hz.

The acoustic drivers will be upgraded to provide a greater pressure field intensity in order to allow other standing wave modes to emerge, such as radial modes. Present observations have shown that as the jet velocity increases, the effect of the applied acoustic field on the spray diminishes. By using more robust acoustic drivers, the mean jet velocity can be increased with the instability effect remaining. In addition, fluids such as Freon 112 and Freon 113 will be used to simulate actual rocket motor fuels and oxidizers.

In terms of measurement techniques, a variety of approaches will be employed including microphone probes for characterizing the induced pressure field, while flash photography, high-speed cinematography, a two-dimensional laser polarization ratio technique, and a laser-based phase doppler particle analyzer will be used to characterize any observed spray instability phenomena. The photographic techniques yield a global view of the interaction between the applied acoustic field and the injected fluid, whereas the laser techniques allow for quantitative measurements of the observed spray phenomena.

A two-dimensional polarization ratio technique is currently being developed to acquire droplet size data under transient combustion conditions. This technique is based on a thin sheet of laser light emanating from a frequency doubled Nd:YAG pulse laser illuminating a spray. The two-dimensional polarization ratio technique determines the droplet diameter in the plane of the laser sheet using the measured polarization ratio of the scattered laser light from spherical liquid droplets in the spray. In essence, the polarization ratio technique gives spatially extensive droplet size data with high temporal resolution.

The phase doppler particle analyzer uses an Ar-ion laser to maintain a non-intrusive probe volume in a given environment and provides a point measurement of the droplet size in the spray. The phase doppler particle analyzer will continuously record droplet size and velocity distributions inside the probe volume with respect to the phase of the acoustic oscillation.

Thus by using the above two laser diagnostic techniques, a quantitative determination of the effect of the induced pressure field on the spray can be obtained. The techniques provide complementary information and measurement verification concerning the evolution of the spray in the oscillating pressure field.

Concurrent with the continued acoustic instability work in the current chamber, a new transparent rectangular chamber will be constructed. One of the difficulties with the current cylindrical chamber is its 'rich' frequency characteristics. By fabricating a chamber in which the consecutive standing wave frequencies are equally spaced, one can easily locate acoustic modes of interest with a standard frequency generator. The transparent nature of the new cell will allow more optical and visual access to utilize the proposed measurement techniques. In addition, the new cell will allow easier access for microphone probes.

The objective of these experiments will be to better understand the interaction between an oscillating pressure field and the atomization and spray phenomena in rocket combustors. Continued attention will be given to the study of the observed coupling between the pressure field and the breakup of liquid jets as described previously in the results section. However, additional attention will be given to the study of droplet-droplet interactions such as coagulation and secondary breakup which may follow the atomization process. These measurements will be conducted under conditions similar to the liquid break-up studies and will concentrate on quantitative droplet size measurements using the described laser-based techniques.

**LIQUID JET BREAKUP
AND
ATOMIZATION IN ROCKET CHAMBERS
UNDER DENSE SPRAY CONDITIONS**

